All the experiments were carried out using the 20 T, 195 mm bore resistive magnet at the NHMFL. The studies are aimed at understanding the systematics of magnetic field induced texture in several high-T_c superconductors. The principle objective is to understand and optimize the various reaction parameters to achieve maximum magnetic field induced texture.

Several samples of $Bi_2Sr_2Ca_1Cu_2O_8$ (Bi2212) superconductor with varying phase assemblages were heat treated in magnetic fields up to15 T. Figure 1 depicts XRD patterns of a bulk $Bi_2Sr_2Ca_1Cu_2O_8$ sample melt processed in a 15 T filed. The presence of strong 00l reflections indicates good c-axis texture in the sample. Figure 2 depicts the microstructure of a diffusion couple reacted in 15 T field.

Figure 2. SEM image of the diffusion couple region of the Bi2212 heat-treated in 15 T magnetic field.

QUANTUM SOLIDS

Magnetism of ^{3}He Nano-Clusters in a ^{4}He Matrix

Adams, E.D., UF, Physics
Matsunaga, N., UF, Physics
Schuberth, E.A., Walther Meissner Institut
Shvarts, V.A., UF, Physics/NHMFL
Xia, J.S., UF, Physics/NHMFL

Simultaneous measurements of susceptibility and pressure have been made in ^{3}He nano-clusters, formed after phase separation of the initial ^{3}He-^{4}He mixture, at temperatures down to 0.5 mK. Pressures were in the range of 3.0 to 3.6 MPa, which produce three different, unique environments for the nano-clusters. At the highest pressure, which is above the melting pressure of pure bulk ^{3}He, the nano-clusters are completely solid, as observed from the pressure measurements. At pressures near 3.0 MPa, the ^{3}He forms as liquid droplets when the phase separation occurs, since the pressures is lower than of pure bulk ^{3}He. Upon cooling to lower temperatures, nano-clusters formed at intermediate pressures undergo partial melting, as observed by the pressure. Susceptibility measurements, using pulsed NMR, of the nano-clusters have been made in all three of these situations, with the temperature measured by pure ^{3}He melting pressure.

The sample studied most extensively was at a pressure of 3.36 MPa, which was observed to undergo partial melting at about 20 mK. From the change in pressure on partial melting, it was determined that a large fraction of the cluster did not melt. One possible explanation for this is that the van der Waals attraction by the more dense ^{4}He produces a dense layer of ^{3}He at the interface that remains solid, with only the center of the cluster undergoing melting. In contrast to pure bulk solid ^{3}He at this pressure, which orders antiferromagnetically at about 0.9 mK, this sample followed a Curie law, $\chi = C/T$, (with a negligible Weiss θ) to the lowest temperature of about 0.5 mK.

The sample at a pressure 3.5 MPa, which showed no melting since it was above the melting pressure of pure bulk ^{3}He, also deviated very little from the Curie law above 1 mK. At lower temperatures, however, there was a gradual increase of χ above the Curie behavior, indicating a tendency toward ferromagnetism. These preliminary results, which have been reported previously,[1-3] must be investigated further.

1   Adams, E.D., *et al.*, J. Low Temp. Phys., **113**, 375 (1998).
2   Matsunaga, N., *et al.*, Proc. LT-22, August 1999, Helsinki, Finland.
3   Adams, E.D., *et al.*, Invited oral presentation, QFS-99, August 1999, St. Petersburg, Russia.

Nonlinear Spin Dynamics of Dilute ^{3}He-^{4}He at Very High B/T   IHRP

Akimoto, H., UF, Physics and Univ. of Massachusetts
Candela, D., Univ. of Massachusetts, Physics and Astronomy
Mullin, W.J., Univ. of Massachusetts, Physics and Astronomy
Adams, E.D., UF, Physics
Xia, J.S., UF, Physics/NHMFL
Sullivan, N.S., UF, Physics/NHMFL

Numerical simulations have been carried out to assess the feasibility of using spin-echo and spin-wave experiments to measure the polarization dependence of transverse and

longitudinal spin diffusion constants of very dilute ^{3}He in superfluid ^{4}He. For high spin polarizations obtainable at high magnetic fields and very low temperatures, the transverse spin diffusion constant is predicted to remain finite at zero temperature.[1,2] This unusual effect results from the special properties of the phase space for scattering given by the space between the spin-up and spin-down Fermi spheres. This effect leads to an anomalous dampening of the spin-echoes.

The results of the simulations show that when the conditions are satisfied for strong spin wave resonances, the spin echoes are difficult to observe because the boundary effects move through the cell. The detailed results, however, show that they do not destroy the magnetization completely. The results of these simulation experiments are being used to optimize the experiments that are being designed to measure the diffusion experiments. Current estimates indicate that the transverse diffusion constant should be able to be measured to within 20% for the planned experimental conditions at B=15 T and T ~ 1 mK.

1 Meyerovich, A.E. and Musselian, K.A., J. Low Temp. Phys., **95**, 789 (1994).
2 Mullin, W.J. and Jeon, J.W., J. Low Temp. Phys., **88**, 433 (1992).

NMR Studies of Quantum Tunneling in a 2D Film of ^{3}He Atoms

Parks, C., UF, Physics
Stachowiak, P., UF, Physics/Univ. of Wroclaw
Sullivan, N.S., UF, Physics/NHMFL

Pulsed NMR studies at moderately high magnetic fields have been carried out to determine the quantum tunneling regime for a triangular lattice of helium three atoms. Boron nitride powder was used as a substrate and adsorption isotherm studies indicated that atomically clean surfaces could be prepared by suitable baking in a high vacuum. The nuclear spin-spin relaxation times, T_2, were measured for a range of atomic coverages varying from a fraction of the 3 X 3 commensurate coverage to 20% beyond full monolayer coverage (incommensurate). The values of T_2 are very sensitive to the atomic motion, and in the temperature range where quantum tunneling occurs one expects to observe a temperature independent T_2.[1] Analysis of the value of T_2 in terms of the spectral densities of the motion yields the value of the atom-atom exchange rates.

We have measured T_2 from 120 to 2400 mK and observe a temperature independent plateau from 300 to 1200 mK for coverages near the expected commensurate 3 X 3 density . We therefore interpret the results as indicating that the relaxation mechanism in this region is determined by the modulation of the dipole-dipole interactions by atom-atom exchange resulting from quantum tunneling. Further studies in the middle of this temperature range were carried out for a series of surface densities. The results showed a remarkable singularity with a sharp reduction in the value of T_2 by a factor of 10 near the

completion of the monolayer coverage. This result is attributed to the effect of the mobility of a small number of excess atoms or vacancies with respect to perfect coverage on either side of the perfect monolayer coverage. The observed density dependence provides a measure of the isothermal compressibility of the lattice in analogy to the Grüniesen constant for exchange in 3D samples. The observation is critically important for calibrating the surface of the sample to be certain of the monolayer coverage.

In addition we observe a small peak in the value of T_2 at the exact 3 X 3 commensurate lattice coverage. This result indicates that the atomic mobility is maximum for this perfect lattice density, and it is these values that are used to determine the mean atomic quantum tunneling rate for a triangular lattice. Experiments are planned to attempt to determine the difference between 3-fold and 2-fold cyclic tunneling rates for this system.

1 Sullivan, N.S. and Chapellier, M., J. Phys. C (Solid State), **7**, L195-197 (1974).

Correlation Effects and Long-Range Ordering of Quantum Rotors in 2D

Sullivan, N.S., UF, Physics/NHMFL
Kim, K., Stanford Univ., Physics

The orientational ordering of quantum quadrupoles whose centers of mass are localized on a triangular lattice is calculated as a function of concentration using the method of restricted traces.[1] This method includes short range correlations up to second order that are important for determining the critical conditions for the long range periodic ordering of axial quadrupoles. These calculations are particularly relevant to understanding recent NMR observations for ortho-hydrogen on a triangular lattice[2,3] which revealed the existence of a critical concentration of 69% below which long range ordering was lost and replaced by a 2D spin-1 glass state at low temperatures. The ortho-hydrogen molecules with orbital angular momentum J=1 behave as ideal quantum rotors in this system.

In Figure 1 we show the calculated temperature and concentration dependences for the order parameter $S=\langle 3J_z^2-J^2\rangle$. S measures the spin alignment for a quantum rotor J, with respect to a local symmetry axes z. The temperature dependences were obtained by explicitly calculating the free energies, and then minimizing with respect to S. At high concentrations there is a distinct jump in the order parameter, signaling a clear first order transition. This jump in S diminishes rapidly as the concentration is reduced. Below a critical concentration of 72% no transition to the long range ordered structure is predicted by this theory. The results are consistent with high sensitivity NMR studies[3] of ortho-para hydrogen mixtures adsorbed as a commensurate 3X 3 structure on hexagonal boron nitride.
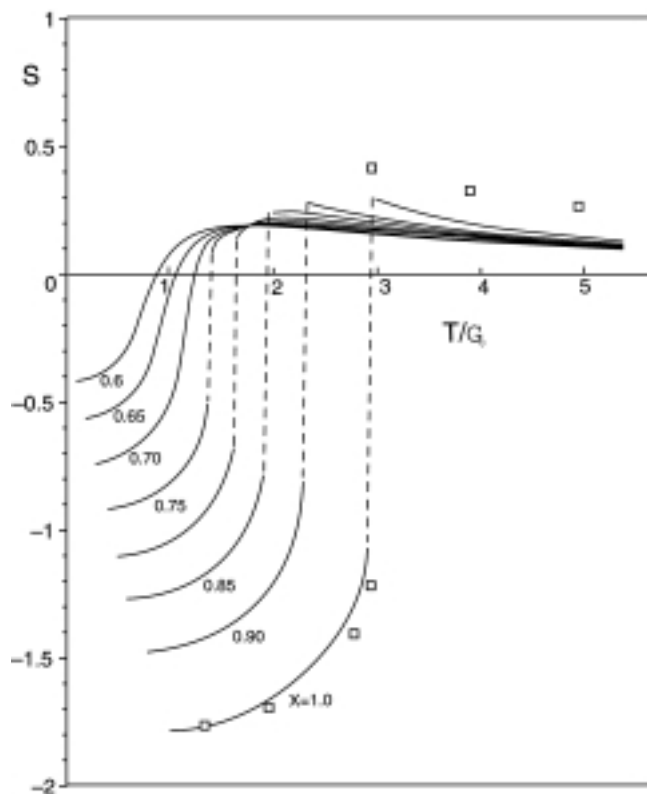
Figure 1. Calculated temperature dependence of the order parameter S for a triangular lattice of spin-1 quantum rotors for several rotor concentrations X. The enhanced quantum zero-point fluctuations result in a high critical concentration of 72% below which long range ordering is not realized. Γ_0 is the quadrupole-quadrupole interaction constant. The squares refer to values of S obtained from NMR spectra.

[1] Kirkwood, J.G., J. Chem. Phys., **6**, 70 (1938).
[2] Sullivan, N.S., and Kim, K., J. Low Temp. Phys., **113**, 705-710, (1998).
[3] Sullivan, N.S., and Kim, K., J. Low Temp. Phys., **114**, 173-201, (1999).

Tunnel Diode Microwave Marginal Oscillator for Magnetic Resonance at High B/T

Tyner, B., UF, Physics
Sullivan, N.S., UF, Physics/NHMFL

We have designed and tested a microwave cavity resonator for the detection of magnetic resonance in the range 650-1700 MHz. The system consists of a high Q-factor (Q>3000) coaxial resonator that is directly coupled to a tunnel diode operated in its negative conductance region. The coupling consists of a small loop located inside the cavity and whose area can be adjusted to match the impedance of the cavity to the magnitude of the negative conductance of the tunnel diode. The tunnel diode itself is mounted on microwave chip capacitors immediately outside the cavity coupling hole. The internal resonant structure of the cavity consists of two coaxial components with different diameters threaded on the same axis, and the frequency is simply adjusted by moving one section with respect to the other.

In order to operate reliably for magnetic resonance observations, the diode must be operated in a marginal condition with the device biased at the threshold of oscillation. This condition is achieved by using a feedback loop to hold the bias fixed with respect to an adjustable reference voltage. As the field is swept through the magnetic resonance condition, RF power is adsorbed from the electromagnetic field in the cavity and the increased load shifts the bias condition for oscillation, and thus the voltage provided by the feedback circuit. A low pass filter network is used in the feedback and the signal before filtering provides the desired output. The advantage of this oscillator is that it measures the pure adsorption signal of the magnetic resonance susceptibility and it can be operated *in-situ* in the magnetic field and down to very low temperatures. The total power dissipation depends on the tunnel diode model chosen, but can be well below 10 microwatts. The circuit has been successfully operated as an EPR spectrometer up to 1700 MHz and would be useful for *in-situ* NMR experiments for magnetic fields up to 50 T and for a wide range of sample temperatures.

[1] Sullivan, N.S., *et al*., Recent Research Developments in Cryogenics, **1**, 23-27 (1996).

Optical Spectra of Quantum Confinement Systems at High Magnetic Fields

Zheng, J.P., FAMU-FSU College of Engineering, Electrical Engineering
Wei, X., NHMFL

The project proposes to apply high magnetic fields to quantum confinement systems as a means to study size distribution effects, multiparticle effects, and interface properties. The proposal goal is to determine a method to enhance the optical nonlinearity and study the excitonic (electron-hole) recombination processes in quantum confinement systems.

Electron-hole recombination in two quantum confinement systems, semiconductor-doped glasses and porous silicon, was measured by optical absorption and photoluminescence
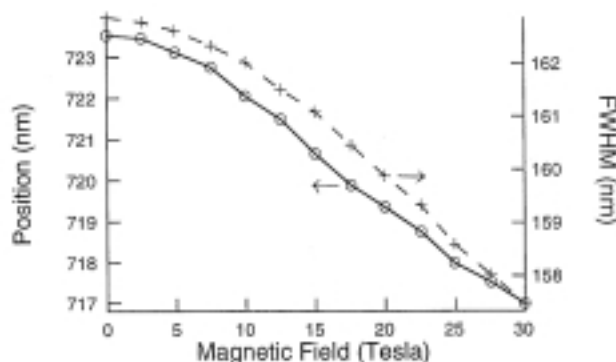

Figure 1. The magnetic field dependence of the position of the peak intensity and bandwidth of PL from a porous silicon sample at 20 K.

(PL) spectra. The electron-hole confinement energy, PL peak intensity and width as a function of the magnetic field were studied under magnetic fields from 0 to 30 T.

Figure 1 shows the position of the peak PL and the bandwidth from porous silicon sample as a function of the magnetic field. The sample was cooled to 20 K and excited by an Argon ion laser at the wavelength of 457.9 nm. The position of the peak PL and the bandwidth represent the energy and its distribution of the band gap, respectively, during the electron-hole recombination. A blue shift in energy band gap and the reduction in bandwidth were observed when the magnetic field was increased. These results confirmed our predication that the

high magnetic field can confine electron-hole orbit to have a uniform confinement energy. Besides the position of the peak PL and the bandwidth, the PL intensity under high magnetic fields was also investigated.

The observation of this study has improved the knowledge of the origin of electron-hole recombination and optical nonlinearity in quantum confinement systems. The project has also involved collaboration within the Department of Electrical Engineering and the NHMFL. The project will help to establish a long-term collaboration relationship in future researches in the field related to optical properties of materials under high magnetic fields.

KONDO / HEAVY FERMION SYSTEMS

Magnetoresistance of Low Carrier Density Hexaborides

Aronson, M.C., Univ. of Michigan, Physics

The recent discovery of ferromagnetism in La doped BaB_6 and CaB_6 (Young 1999) has renewed interest in the properties of the low density, three dimensional electron gas. While it has not yet been directly demonstrated, it is thought that stoichiometric RB_6 (R=Ca, Sr, Ba) are semimetals, with overlap of the conduction and valence bands at the X-point. It is possible to vary the band overlap, and thus the carrier concentration, by decreasing the alkali earth concentration in the starting material, or by doping with a trivalent element such as La. In the experiment reported here, we have studied five different samples of RB_6 that are expected to have carrier concentrations that range from that of stoichiometric RB_6 to the range of carrier concentrations for which ferromagnetism is observed in La-doped RB_6. We have carried out magnetoresistance and Hall measurements in these samples in the 60 T short pulse magnet.
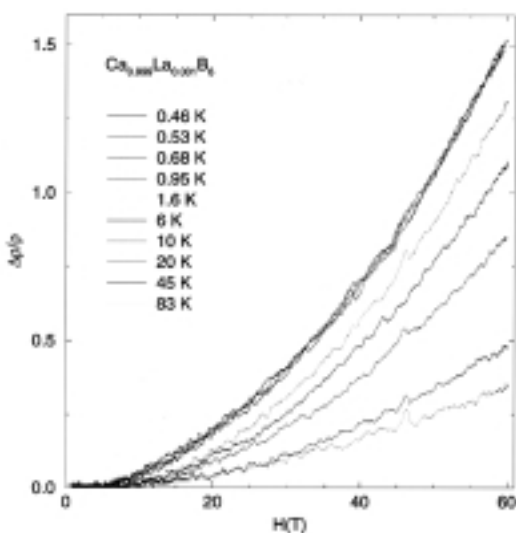

Figure 1. Magnetoresistance of CaB_6 with 0.1% La, for temperatures from 0.45 K (top) to 83 K (bottom).
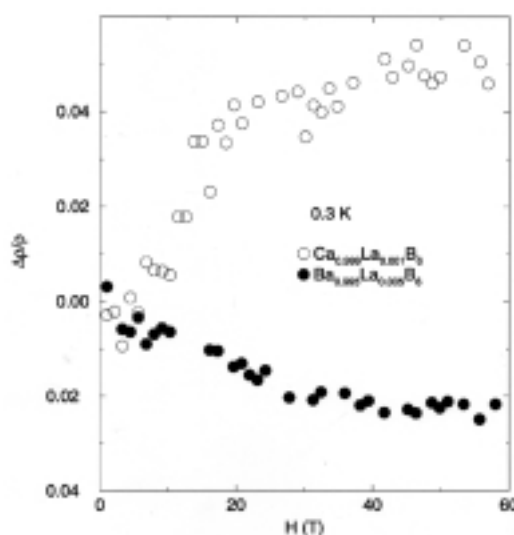

Figure 2. Comparison of the transverse magnetoresistance for two samples with different carrier concentrations.

An example of our results is given in Figure 1. We find a large positive magnetoresistance in each sample, which is approximately quadratic in field. Similar field dependences have been found in other hexaboride compounds (Cooley 1997, Aronson 1999). As in those cases, the magnitude of the magnetoresistance increases with decreasing carrier concentration, as expected from Kohler's rule. In addition to this positive magnetoresistance, we have also identified an additional contribution to the magnetoresistance in low fields, which is even more strongly sensitive to the carrier concentration of the sample. These contributions are plotted in Figure 2 for each sample. Since the magnitude of this contribution varies dramatically from sample to sample, as does the sign, we speculate that this is actually a Hall resistance. Unfortunately, we were not able to reverse the field direction to test this hypothesis.

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Cooley, J.C., et al., Phys. Rev. B, 52, 7322 (1995).
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